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Effect of activator type and content on properties of alkali-activated slag mortars

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A R T I C L E   I N F O

A B S T R A C T

Investigation of alkali activation of Turkish slag (AAS) was carried out using sodium silicate and sodium hydroxide activators within the scope of this study. The objective of the present work is to determine the SiO_2/Na_2O ratios (M_S) and Na_2O contents of the solutions on the development of workability, setting times, mechanical properties, drying shrinkage, water absorption characteristics and microstructure of alkali activated slag cement binders. Test results showed that M_S and Na_2O contents of activator solution are of great importance on the properties of AAS. Portland cement free high performance composite with compressive strength values about 100 MPa can easily be achieved by activation of slag without heat curing. Moreover, in case of activation by optimum M_S ratio, sodium silicate activated AAS mortars present higher compressive strength, lower water absorption, higher workability, lower porosity and a wide range of setting times compared to NaOH activated AAS mortars and Portland cement mortar. Consequently, it can be said that this new binder is likely to have enormous potential to become an alternative to Portland cement.

1. Introduction

Ground granulated blast furnace slag (GGBFS) is a by-product of steel production. It has been reported that, slag generation is about 10% of the total production. Blast furnace slags are usually utilised in construction industry in the production of blended cements and concretes. However, only small amounts (20–30%) of slags are utilised in this area and the rest is stored in large volumes [1]. The production of high performance alkali activated slag (AAS) based composites may be an alternative utilisation area of this by-product.

Utilisation of GGBFS in this area has significant environmental and economical benefits since its production requires less energy than the production of Portland cement. And there is no CO_2 emission to the atmosphere during this process. Besides these environmental and economical benefits, AAS binders present some important technical advantages over ordinary Portland cements. These can be listed as; the development of earlier and higher mechanical strengths, lower heat of hydration, low porosity, low solubility of the hydrates, stronger aggregate–matrix interface, and superior durability. However, they also have some disadvantages such as rapid setting, high shrinkage, subsequent formation of microcracks and higher formation of salt efflorescences. Further-

more, questionable results exist about alkali–aggregate reactions and carbonation [2–4].

Since rather early discovery of alkali-activated cements and concretes in 1958, they have been commercially produced and used in limited construction projects in the former Soviet Union, China and some other countries. AAS have been used in the construction of drainage anti-soil slipping collector/tubing, silage trenches, slopes of railway embankment, high storey residential buildings, special concrete pavements for heavy loaded trucks, pre-stressed reinforced concrete slippers for railways, masonry blocks, oil-well concreting, refractory concrete, stabilization and solidification of hazardous and radioactive wastes, etc. Various inspections during 1999–2000 years showed that in all these structures, the performance of alkali-activated slag cement concrete was superior compared to the Portland cement concretes used in the same area [5]. However, AAS is not a well-known binder in Turkey besides a very limited research.

Superior mechanical properties have been reported for AAS binders. In China, compressive strength of 60–150 MPa for AAS concrete activated by waterglass was achieved without heat treatment or special additives [6]. Zivica et al. reported a compressive strength of 150 MPa for alkali-activated slag paste prepared with alkali activator solution: slag ratio of 0.08 and pressure compaction in fresh state [7].

Activation process of slag varies with the chemical properties and phase compositions of slags, the type and concentration of activators. Slags have a variable composition depending on the

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raw materials and the industrial process; hence, each slag response differently to the activation process. For every slag it is necessary, to plan a research program for determining the most suitable activator type and content. Sodium hydroxide and sodium silicate (water glass) are the most commonly used activators. Sodium silicate is also considered the most effective activator. The most important properties of water glass are the ratio of SiO_2/Na_2O and Na_2O content. The aim of this study is to determine the effect of these parameters on the activation of a Turkish slag in respect to the mechanical properties, microstructure, workability, setting times, water absorption and shrinkage characteristics.

2. Materials and experimentation

Ground granulated blast furnace slag procured from Ereğli steel plant has a chemical composition presented in Table 1. Specific gravity and specific surface (Blaine) of GGBFS is 2.88 and 410 m^2/kg, respectively. It contains, 90% particles sized lower than 45 μm. It is neutral with the basicity coefficient $[K_b = (CaO + MgO)/(SiO_2 + Al_2O_3)]$ of 0.81. As can be seen from Table 1, the hydration modulus $HM = (CaO + MgO + Al_2O_3)/SiO_2$ of slag is 1.33.

Ordinary Portland cement (CEM I 42.5R) with a Blaine fineness of 369 m^2/kg has been used as reference binder. Chemical composition of Portland cement (PC) has also been presented in Table 1.

Alkali activated slag (AAS) mortars were produced by activation of GGBFS with technical grade sodium hydroxide and water glass (liquid sodium silicate). Sodium silicate used in this study has a 27% and 8% of SiO_2 and Na_2O contents, respectively and with a M_S value (SiO_2/Na_2O) of 3.38. Sodium hydroxide and sodium silicate were mixed in various proportions, within the M_S range of 0.4–1.6. Also, solutions with M_S equal to zero have been prepared by using NaOH alone. AAS mixtures with Na_2O contents of 2%, 4%, 6%, and 8% were investigated after pre trials. Activator solutions were prepared 1 day before casting of the mortars.

Twenty different alkali-activated mortar mixtures and a control PC mortar mixture were prepared with crushed limestone sand (0–4 mm). Aggregate to binder (PC or GGBFS) ratio of 2.75 was kept constant for all mixtures. Water to binder ratio of all mixture was 0.44. All test batches were mixed by using an electrically driven mechanical mixer conforming to the requirements of ASTM C305 [8]. Initially, binder and aggregate were mixed in a dry state for 1 min and then the solutions were gradually added during mixing for about 3 min. The flow test was performed according to ASTM C230 [9]. Fresh mixtures were cast into prismatic (40 × 40 × 160 mm and 25 × 25 × 285 mm) steel moulds. The specimens were kept in the moulds in the humidity cabinet for 24 h at about 20 °C and a relative humidity of 90%. After demoulding, specimens were kept in water at a temperature of 20 °C until the testing periods.

The prismatic specimens (40 × 40 × 160 mm) were subjected to flexural strength test according to ASTM C348 [10]. Three specimens were tested and average values were recorded. The specimens were loaded from their mid-span and the clear distance between simple supports was 120 mm. The compressive strength tests were performed according to ASTM C349 [11]. Shrinkage measurements were performed on mortar bars (25 × 25 × 285 mm) according to ASTM C596 [12]. Specimens

Table 1
Chemical composition (%) of GGBFS and cement.

	SiO₂	Fe₂O₃	Al₂O₃	CaO	MgO	Na₂O	K₂O	SO₃	LOI
GGBFS	40.20	1.68	11.66	35.90	5.88	0.30	1.47	0.90	0.88
PC	19.10	3.96	4.40	61.85	2.05	0.27	0.70	3.72	1.82

were demoulded 24 h after casting and cured in water for 48 h. The first reading of length was taken at the age of 72 h. After the first reading, the prisms were placed in laboratory (~20 °C temperature and 55% relative humidity). Length changes of prisms were measured periodically up to 6 months. Capillary water absorption of mortars was determined according to ASTM C1403 [13]. Water absorption and volume of permeable voids of mortars were also determined according to ASTM C642 [14]. Initial and final setting times were determined by using a Vicat apparatus according to TS EN 196-3 [15]. The water/binder ratio of all the pastes was kept constant at 0.33.

3. Results

The effectiveness of M_S and Na_2O content of solution on the activation of GGBFS was investigated by various tests on different mortar mixtures. Test results are discussed below:

3.1. Workability

Flow values of fresh mortars according to their M_S and Na_2O values are given in Fig. 1 together with control PC mortars. PC mortars are marked by dash line in all figures. As can be observed from Fig. 1, most of the AAS mortars present higher workability than PC mortars. Also, flow values of mortars increased parallel to the increase in M_S at relatively low Na_2O contents (2% and 4%). However, at higher Na_2O contents this trend was not observed especially in $M_S = 0.4$ and 0.8. For $M_S = 0$ case, higher Na_2O contents resulted in better flow values.

3.2. Setting times

Initial and final setting times of pastes for various M_S and Na_2O values are presented in Fig. 2. Setting times of AAS pastes varied in a wide range. Initial setting times were recorded in the range of 2–326 min, while final setting times were 2–442 min. It should be stated that, standard consistencies of (6% Na_2O, $M_S = 0.4$ paste) and (8% Na_2O, $M_S = 0.4$ and 0.8 pastes) were between 20 and 31 mm. The standard consistencies of the other mixtures were lower than 7 mm, similar to PC paste's consistency.

For 4% Na_2O mixture, higher M_S ratios caused a slight reduction in the setting times (Fig. 2). For mixtures with 6% and 8% Na_2O contents, setting times of pastes decreased dramatically for $M_S = 0.4$ and 0.8. These mixtures seem to be not appropriate for normal construction works. However, they may be very appropriate for the works that needs quick setting, such as shotcrete. The faster setting of AAC by sodium silicate may be attributed to the formation of an
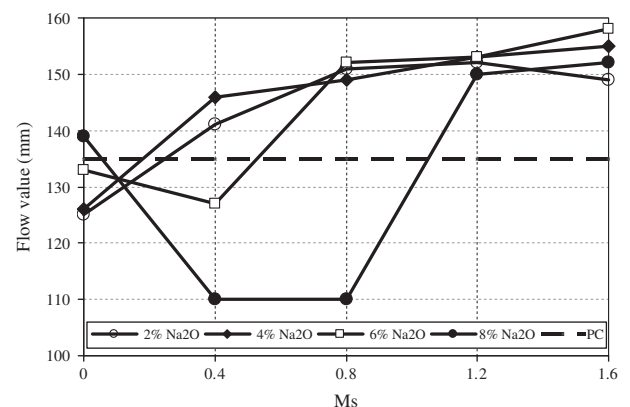

Fig. 1. Flow values of mortars.